time productivity of the soil—practices must be used to maintain within the soil conditions similar to those in the natural Chernozem. This means abundant plant nutrients and good structure for considerable depth. Such a deep layer of fertile soil with good structure often needs to be made by the farmer from the natural soil. An individual set of practices to this end will be required in each individual landscape.

With the proper practices, grasses can be grown efficiently in most parts of the world, but not everywhere. One of the great problems of agricultural science is to learn how to make these practices more efficient and especially how to adapt them more precisely to the individual soil types. Then too, we need to discover practices for growing good grass efficiently on those soils for which we have as yet no satisfactory methods.

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HOW SOILS DEVELOP UNDER GRASS

JAMES THORP

RELATIONSHIPS between grassland soils and their dominantly grassy cover are close and complex. The soils owe many of their properties to the kinds of vegetation they support; the kinds and qualities of grasses and associated plants depend considerably upon the characteristics of the soil.

Native dense stands of tall grasses in the United States usually have produced thick, dark-colored soils, high in fertility and suitable for growing many economic crop plants, especially members of the grass and legume families.

Less luxuriant grasses in drier areas have produced lighter colored soils with less organic matter and nitrogen, but frequently with more mineral plant nutrients than those of tall-grass regions. The variety of adapted crops on these soils is narrower, and yields are limited by the lower rainfall, except where crops are irrigated.

In the *Atlas of American Agriculture,* 1936, H. L. Shantz said this about the location and conditions in the United States under which grasslands develop: "Lying between the western and eastern forest belts, and extending from Canada on the north to Mexico on the south, is the great grassland area, broken only by river courses and occasional buttes or low mountains.

"Grasslands characterize areas in which trees have failed to develop, either because of unfavorable soil conditions, poor drainage and aeration, intense cold and wind, deficient moisture supply, or repeated fires. Grasses of one kind or another are admirably suited to withstand conditions of excess moisture, excess drought, and fires which would destroy tree growth."

Important smaller areas of grassland in this country occur also on the Coastal Plain of Alabama and Mississippi, in north-central Oregon and southeastern Washington, in the Central Valley of California, and in hundreds of narrow strips along the mountains and basins from the eastern limit of the Rocky Mountains to the Pacific coast.

The type of grass and the density of cover—both important to soil formation—are determined by the interaction of many factors. For example, rank water-loving grasses and sedges and other grasslike plants grow in poorly drained areas and contribute enormous quantities of organic matter to soils of marshy and semimarshy lands. Wiesenboden [1] (wet meadow soils) and Half Bog soils develop in these situations.

The well-drained black Prairie and Chernozem soils have thick covers of sod-forming tall-grass associations. Heavy, dark, grayish-brown clay soils like the Pierre clay developed from Pierre shale of South Dakota and northwestern Nebraska seem to provide conditions where western wheatgrass is best able to survive as the dominant grass. Shantz's map of the grasslands of the United States, in the *Atlas of American Agriculture,* shows an area of western wheatgrass coextensive with a large area of Pierre clay soil. On very sandy soils, as in the sand hills of Nebraska, are associations of sand sage and sand reedgrass with bluestem grass. Farther south, as in sandy soils of Texas, a low scrubby growth of shinnery oak is associated with bunchgrasses.

Blue grama appears to be the dominant grass of medium-textured soils in the zone of Brown soils from Colorado to the Canadian line, while mixed grama and buffalograss are widely distributed in the dry parts of the Chestnut and Reddish Chestnut and the Reddish-Brown soils zones. Red Desert soils and some areas of Reddish-Brown soils in New Mexico and western Texas are dominated by black grama grass, associated with other grasses and desert shrub.

The formation of grassland soils involves the accumulation of mineral soil materials, the invasion of these materials by grass, and the accumulation of organic matter and development of soil structure.

Mineral soil materials accumulate through the direct chemical and physical weathering of rocks and through the deposition of broken and chemically weathered rock fragments (sand, silt, clay, and gravel) by streams, lakes, glaciers, wind, and down-slope gravitational movement. A very rough estimate is that one-third to one-fourth of the soil materials of the natural grasslands in the United States are the products of direct weathering of rocks of greatly varying composition and hardness. The remaining materials have been deposited by streams and the other agencies I have listed.

The larger areas of grassland soil materials, developed directly through the weathering of rock, came from soft rocks that either were weathered easily to form soil or were already soft enough in their original state to be penetrated easily by the fibrous roots of grasses. The great area of Pierre shale in South Dakota, Colorado, and Nebraska, and the still larger areas of tertiary shales, silt-stones, and soft sandstones of Montana, North Dakota, Wyoming, Colorado, and Utah are good examples.

The extensive loess (wind-blown dust) deposits of the Great Plains east of the Rockies and of the Palouse region of Oregon and Washington are ideal for the growth of grass. Loess is a uniform unstratified mixture of silt, very fine sand, and clay. It varies in thickness from a few inches to more than 100 feet in the United States. Probably loess is the most extensive single kind of parent material of grassland soils in the world as a whole.

Glacial deposits composed of clay, sand, silt, and stone fragments of many kinds are parent materials of thousands of square miles of grassland soils of the northern Great Plains of the United States and of the Great Plains of Canada. Possibly wind-laid and water-laid sands are third in im-

[1] Throughout the text of this paper references are made to great soil groups, as Prairie, Chernozem, Wiesenboden, Chestnut soils, Brown soils, etc. These are described by C. F. Marbut in the *Atlas of American Agriculture,* 1936, and redefined and (in part) renamed in the chapter on soil classification in the *Yearbook of Agriculture 1938.* Prairie soils, for example, do not include all grassland soils but are restricted in the United States largely to the Corn Belt.

portance. For example, the grassy sand hills of Nebraska are only slightly smaller in area than all of the cultivated land of Japan, and very large areas of aeolian sands occur in Kansas, Colorado, Wyoming, Oklahoma, Texas, Oregon, and Washington.

Stream alluvium and lake sediments of medium to clayey textures also are important, especially along the large river valleys and mountain fronts.

Where climatic conditions are favorable, grass invades areas of freshly deposited soil materials very soon after they are first exposed. If accumulation of sediments or weathered rock materials is slow, grasses become well established and begin immediately the work of soil building. Roots spread through the soil and sooner or later die, providing organic, humus-forming waste.

Indeed, where the accumulation is slow, soil formation can almost keep pace with weathering and deposition, and upper soil layers rapidly take on a dark color. Where accumulation of soil material is rapid, as is true of some sedimentary deposits, vegetation has relatively little effect on soil development until accumulation slows down or stops. Plants are covered before they can contribute much to the soil.

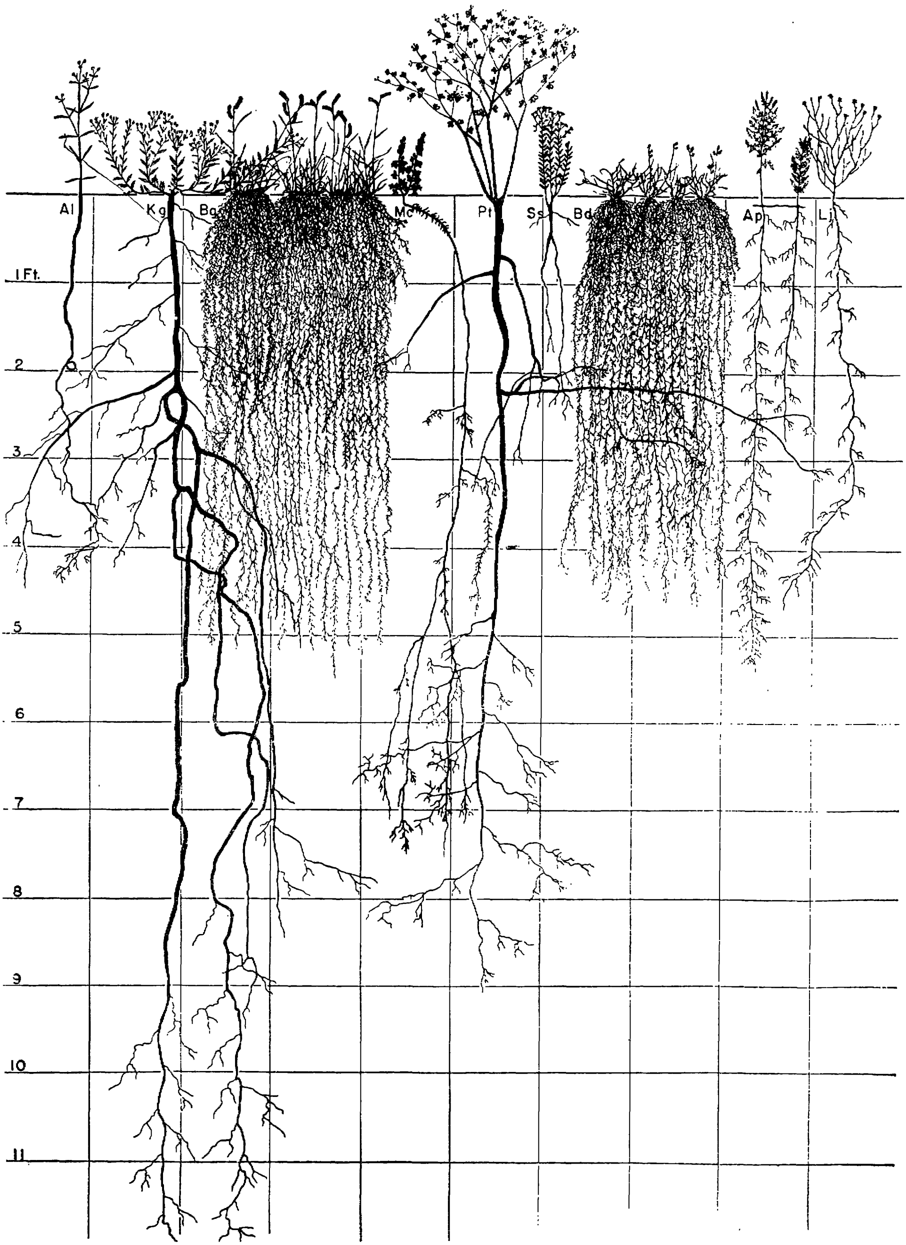
Abundant geologic evidence in large areas of grassland in the United States shows not only that the stream sediments and wind-laid dust (loess) and sand are extensive, but also that many of them accumulated so rapidly that soil formation did not advance appreciably until the deposits were almost complete. Furthermore, buried remnants of soils, in some places one above another, show that the history of soil formation has been repeated many times. Waves of catastrophic erosion have advanced across the land, destroying strongly developed soils and concurrently building up new deposits of alluvium, loess, or sand. Local accumulation of sediments has been so rapid that soil formation could not keep pace, and soil development has been delayed until the rapid erosion and deposition have abated.

Even now, the opposing processes of erosion and deposition are working in the grasslands of the United States. In the Badlands of South Dakota, Wyoming, and Montana, for example, catastrophic erosion is rapidly eating away the cliffs of soft bedrock and dumping sediments indiscriminately on the lowlands and along the stream courses. After the first big wave of deposition has subsided, grasses and other plants take root quickly on smooth land below the Badland cliffs and a new cycle of soil formation begins on the fresh deposits. High grasslands behind the cliffs, meanwhile, are undermined and destroyed.

When grasses and other herbaceous plants secure a foothold, the soil materials are held in place by a network of roots. Old roots die and new ones take their places. Dead roots are attacked by bacteria, microscopic animals, and fungi, and mineral and organic nutrients are made available to living plants. Under the climatic and biotic conditions of grasslands, part of the root material, as well as part of the annual crop of grass tops, remain to form dark-colored, finely divided organic matter (humus) in the soil, and a larger part is absorbed by other plants or dissipated into the air as gas or into the soil water and carried away.

Organic material in grassland soils, then, includes living and dead plant parts, living and dead organisms, and humus. The decay of grass roots and leaves and the formation of humus so improve the fertility, physical condition, and moisture-holding capacity of the soil that more luxuriant grasses will survive as time goes on. Light-colored soils, shallow to the underlying parent soil material, which are characteristic of the first stages of development, are thickened and darkened gradually with the improvement of the grassy cover. The end point of this process varies with the moisture supply.

As soon as vegetation is established, many kinds of animals take up their abode in the soil to take advantage of the food provided by plants or to prey



Roots of different grassland plants draw their moisture from different soil layers. Some native plants extend their roots to depths of 20 or more feet. Drawing made at Hays, Kans., before the great drought, by J. E. Weaver and F. W. Albertson (Ecol. Monographs, volume 13, p. 100). *Al,* narrow-leafed 4-o'clock, *Allionia linearis; Kg,* prairie false boneset, *Kuhnia gultinosa; Bg,* blue grama, *Bouteloua gracilis; Mc,* globemallow, *Malvastrum coccineum; Pt,* a legume, *Psoralea tenuiflora; Ss, Sideranthus spinulosis; Bd,* buffalograss, *Buchloe dactyloides; Ap,* western ragweed, *Ambrosia psilostachya;* and *Lj,* skeleton weed, *Lygodesmia juncea.*

on one another. Insects (especially ants), millipedes, earthworms, gophers, prairie dogs, and many other animals live interdependent lives in the soil. Their burrowing operations stir the soil, mix it with fresh minerals, kill some roots, and hasten the process of humification. The soil becomes a community of teeming activity.

Organic matter in grassland soils acts as a sponge to absorb rain water, as a home and as food for the microscopic plants and animals that prepare the soil for the use of higher plants, and as a water reservoir to supply plants with needed moisture and to cushion them against drought. Much of the all-essential nitrogen is stored in the organic material waiting to be made available by micro-organisms for the use of higher plants.

Field studies of grassland soils that range in age from a few years to a probable age of many thousand years indicate that organic matter accumulates somewhat slowly during the first few years until a good relationship for the formation of organic matter is reached among the microscopic plants and animals, the higher plants, and the higher animals that live in the soil. Following the establishment of this favorable relationship, the rate of accumulation increases rapidly for many years and more slowly after that. In medium-textured soil materials of well-balanced mineral composition, it is thought that the maximum content of organic matter will be attained in several hundred years.

Ultimately some rough balance is reached between the rate of accumulation and destruction of humus and between types of grasses and forbs present and the degree of their luxuriance. The level at which this rough balance is struck depends on the texture, porosity, and plant-nutrient content of the soil material and on the amount of easily available moisture received, absorbed, and retained by the soil for use of plants. This balance is a dynamic one, subject to minor fluctuations, and probably is maintained under natural conditions for a few thousand years.

During periods of greater-than-normal humidity, the grasses are more luxuriant and contribute more organic material to the soil; leaching goes to a greater depth than in dry years, and some of the soluble compounds are carried out in subsoil water. In most grasslands, both wind and water erosion are reduced during years of abundant rainfall because the luxuriant vegetation can better hold the soil in place.

During dry periods, grass cover may be largely destroyed if the droughts are prolonged, and contribution of organic matter to the soil may be stopped temporarily. Erosion by wind and water becomes active during or immediately following these dry periods, and organic matter is lost that took years and years for accumulation.

Grasses have a profound effect on the structure of soil. Organic matter from the decomposition of grassroots and leaves helps to hold clay, silt, and sand particles together to form structure particles or aggregates of various shapes, sizes, and degrees of firmness. Generally the upper layers of grassland soils, where roots are most abundant, attain an extraordinary degree of granulation in which the structure particles take the form of firm granules or porous crumbs ranging from less than one-thirty-second of an inch to a half inch in diameter. Some of these aggregates, especially those containing more than about 30 percent clay, are firm and hold their size and shape even with rough handling; others, especially those containing much sand and silt and little clay, are soft, porous, and unstable. The development of granular structure makes the clayey soils of grasslands crumbly and friable and almost as easily tilled as sandy soils.

In all but the very sandy soils, the structure particles of subsoil layers (roughly, the layers lying between 10 and 30 inches below the surface) usually are coarser, more angular, and firmer than those of the upper soil layers, partly because many of them are more clayey and partly because they contain less organic matter.

Some of these structure particles are angular and blocky, others are more or less rounded and nut-shaped, and still others take the form of small prisms. They have less organic matter than the surface layers and usually are held together by thin films composed of jelly-like clay mixed with organic matter. Probably the shape, size, and arrangement of the subsoil structure particles are related partly to shrinking and swelling caused by changes in moisture conditions, and partly to the wedging action of roots that penetrate deep into the soil in search of moisture.

Once the pattern of soil structure is established, many of the grass roots work their way into minute crevices where they expand with growth and press the structure particles into a still firmer consistence. Where clayey soils swell and shrink greatly with changes in moisture, roots are sometimes unable to expand in the normal way and so take on flattened shapes. Some roots do not confine themselves to the crevices but pierce the structure particles and so tend to make them more porous or to break them into smaller units.

Although soils are considered to reach equilibrium with their environment, it is probable that soils of the grasslands gradually change with time. Mineral plant nutrients are removed slowly in solution from subhumid grasslands (Prairie and Chernozem soils). The clay content of the soils is gradually increased by chemical processes, and is concentrated in subsoil horizons where it impedes water movement in the soil and makes soil water less quickly available to plants. In other words, a slow deterioration sets in as soils become older.

In a few places natural erosion and soil formation seem to have reached a balance that keeps the soils fertile and productive for a long time. Generally, however, it appears that soils are either improving gradually through the slow accumulation of organic matter and fresh sediments, or are deteriorating slowly with the aging process. Plowing and cultivating the soil may either increase the rate of improvement or hasten deterioration. Good husbandry improves the land for man's use and raises the level of fertility and productivity. On the other hand, because the nutrient requirements of cultivated plants are different from those of the native grasses, nutrient deficiencies may be expected to develop. In Illinois, Iowa, and eastern Nebraska and Kansas, for example, farmers are already beginning to obtain benefit from the use of superphosphate on some of the older soils.

A large proportion of the Chernozem, Chestnut, Reddish Chestnut, Brown, and Reddish-Brown soils of the Great Plains and of the Pacific Northwest probably had been in a state of temporary dynamic equilibrium for a few thousand years when the region was invaded by white colonists. Most of the Chernozem and Reddish Chestnut soils and a smaller proportion of the others have been plowed and planted for two or three generations, and it cannot be denied that much of the soil has deteriorated under this regime. Some of the organic matter has been lost by wind erosion, some has been oxidized, and some has been washed away. And crops also have made serious inroads on the supply of easily available plant nutrients. Soil management practices are now in a state of slow evolution that we hope will eventually correct a bad situation.

Development of Soils

The dark-colored Prairie and Chernozem soils, with the associated Wiesenboden (dark-colored wet meadow soils) and Planosols (soils with claypan), show the maximum effects of true grasses and other grasslike plants on soil formation. These soils occur in subhumid and dry-subhumid areas where climatic conditions are generally better suited to the growth of grasses than to forest, but where moisture is sufficient to support a dense growth of grass. In the Prairie soils zone, forests will spread over the grasslands fairly readily if young trees are protected from fire until they are well established. Trees can also be made to grow on medium- to sandy-textured soils in the Chernozem soils zone, and even in drier areas, with still greater care; but it is doubtful whether any extensive forest could establish itself on these soils with or without the aid of man. Only on steep north- or east-facing slopes and along stream valleys do forests obtain a permanent foothold in zones of Chernozem and Chestnut soils.

Parent materials of Chernozem and Prairie soils are developed from a very wide variety of rocks, loess, aeolian sand, and alluvium, but loess, glacial drift, alluvium, and soft sedimentary rocks comprise the greater part. Most of the parent materials are calcareous (contain carbonate of lime) or have been in the recent geologic past.

Typical soils of these groups are all well drained, either because of moderate slopes or because substrata are porous and permeable to water and have suitable natural outlets to remove excess water. The land surface ranges from level to gently sloping. Soils of other groups occur on the steep slopes and in wet depressions.

Prairie and Chernozem soils support a natural cover of tall prairie grasses dominated by a few species, with a minor constituent of legumes and other shrubby perennial and annual plants that are not true grasses. Under virgin conditions the original tall-grass cover formed a dense sod at the surface of Prairie soils, but the cover was less complete in the drier parts of the Chernozem soils zone where bunchgrass associations are the rule.

While Prairie and Chernozem soils have in common dark colors, much organic matter, and similar structure, they differ in one important respect: Prairie soils generally are acid in reaction and have lost most of their original carbonate of lime through leaching. Rainfall provides enough moisture nearly every year to pass entirely through the profile. Chernozem soils generally are neutral or slightly alkaline in reaction and typically have a horizon, or layer, of subsoil enriched with carbonate of lime. This horizon is developed because rain water frequently is insufficient to pass entirely through the soil. Percolating water usually reaches only a few feet into the subsoil, where it gradually evaporates into the soil air or is picked up by grass roots and carried back to the surface and transpired through the leaves. Soluble material like carbonate of lime is thus carried to the subsoil and left behind when the water is dissipated.

It is generally true on the Great Plains of the United States and Canada that grassland soils in the cool regions have more organic matter than those in the warmer regions. Soils in subhumid grassland areas of Texas generally have less organic matter than those in areas of southern Manitoba and North Dakota where effective soil moisture is comparable.

After an exhaustive study of the nitrogen and organic matter of hundreds of soils in the United States, Hans Jenny, in *Research Bulletin No. 152* of the Missouri Agricultural Experiment Station, drew a number of conclusions regarding the accumulation of soil organic matter in relation to climate. Among them are:

1. Within regions of equivalent effective moisture, the nitrogen and organic matter contents of soils of medium textures increase 2 to 3 times with every 18° F. fall in average annual temperature, from south to north in the United States. The statement holds for both forested and grassland soils.

2. Within regions of equal average annual temperatures, the nitrogen and organic matter content of grassland soils increases with increasing humidity. The rate of increase is greater in the cool northern regions than in the warmer southern regions. This conclusion does not hold for forested soils.

3. From data available to Jenny at the time his bulletin was written in

1930, he felt that climate and vegetation were more significant to the accumulation of nitrogen in loamy soils than topography, parent material, or age of the soil.

Those who have studied the grass roots in the Great Plains tell us that different kinds of grasses and associated herbaceous plants distribute their roots in different layers of the soil. Some species have concentrated their roots in the uppermost layer where they depend on moisture from rains which penetrate the soil only to a relatively shallow depth. Other plants draw their water from intermediate layers. Still others reach down to obtain water from the deep layers of the parent material and even from the ground water, many feet below the surface. Most of the deepest-rooted plants of the prairies are perennial herbaceous or shrubby plants (known technically as forbs) that grow in close association with the grasses. In times of protracted drought, many of these plants survive while some of the grasses with shallower roots die.

Prairie and Chernozem soils have deep, nearly black surface soils with well-developed granular or crumb structure and much organic matter. Fertility is high. The dark surface layers, under natural conditions, are matted with grass roots to depths of 1 or 2 feet, and many grass roots penetrate to depths of 5 to 8 feet.

J. E. Weaver and others estimated that 60 percent of the underground parts of little bluestem grass on Lancaster loam in Nebraska were in the top 6 inches of soil and that 68 percent of underground parts of big bluestem grass were in the top 6 inches of Wabash clay loam.

S. B. Shively and Dr. Weaver report that the top 6 inches of Prairie soils in western Iowa and eastern Nebraska contain from about 4.5 to about 2.6 tons of underground plant parts (dry weight) per acre, and Chernozems from 2.34 to 2.6 tons per acre in Nebraska and Kansas. Big bluestem produced a larger amount of underground plant parts than little bluestem in the same region. In the same soil, the dark humified organic matter ranges from about 25 to about 40 tons in the top 6 inches of soil on each acre.

Analyses of Prairie and Chernozem soils in North Dakota, Manitoba, and Saskatchewan show that the weights of humified organic matter are considerably greater in the northern parts of the Plains and range from about 40 to possibly 100 tons an acre in the top 6 inches of Manitoba and Saskatchewan soils. In warmer southern areas, total weights of humified organic matter to the acre of the dark-colored Reddish-Prairie and Rendzina soils average considerably less than in Nebraska—roughly 10 to 20 tons in the top 6 inches of soil, on the basis of very limited information.

C. C. Nikiforoff estimates totals of from 120 to 240 tons of humus an acre in Chernozem soils of the United States. His maximum figure is for the entire profile of Chernozems with exceptionally thick dark surface soils.

Dr. Weaver and Ellen Zink have estimated the rate at which roots of various perennial grasses die in the soil under various conditions. The estimates were based on periodic examination of a large number of roots banded with soft tin strips. They found that big bluestem lost 19 percent of its original coarse roots in 3 years, little bluestem and porcupinegrass each 90 percent, blue grama 55 percent, and side-oats grama 86 percent.

All the losses were gradual, and replacements doubtless were made by the plants, but it is interesting that even the relatively long-lived big bluestem roots are able annually to contribute about 312 to 540 pounds of raw organic matter an acre to the top 6 inches of soils in western Iowa and eastern Nebraska and Kansas, assuming pure stands of this grass. This would mean that from about 520 to 900 pounds per acre of raw organic matter is added annually to the entire soil profile.

L. E. Andrew and H. F. Rhoades analyzed a sample of soil developed in calcareous glacial till thrown out from a railroad cut in Lancaster County, Nebr., 75 years ago. Organic matter is most concentrated in the topmost 2 inches of soil, which contains 4.3 percent. Possibly part of this organic matter came from wind-blown dust. The average for the top 6 inches is about 2.9 percent. Assuming that 0.4 percent of the material deposited with the recent dust or present in the original material was organic material, it seems safe to estimate that organic material accumulated in the last 75 years comprises 2.5 percent of the top 6 inches of soil. Assuming further a volume weight of about 1.1 for this layer, the total estimated weight of dry organic matter per acre to 6 inches is about 18.7 tons. At a uniform rate of accumulation, this would be 500 pounds a year. The figure seems high and suggests that organic accumulation might reach its maximum for the region within as little as 200 or 300 years. With a diminishing rate of accumulation, the period might be somewhat longer. The development of a clayey subsoil would take considerably longer, perhaps a few thousand years.

Traveling from east to west across the Great Plains, from subhumid to semiarid or arid climates, one can observe a gradual decrease in the darkness and thickness of the surface soil. The horizon of carbonate of lime lies at shallower depths than in Chernozem soils and is proportionally thicker on soils of equal age and like parent material. These changes correspond directly with the decrease in the height and concentration of grasses on the soil, as well as with the decrease in effective moisture.

Virgin areas of dark grayish-brown Chestnut and dark-brown Reddish Chestnut soils occur under a mixed cover of tall, medium-height, and short grasses, with a considerably less dense cover on the ground. Moisture is not sufficient in the zone of Chestnut and Reddish Chestnut soil to support the luxuriant growth of tall grasses characteristic of the Prairie and Chernozem zones. The Chestnut-soils zone grades imperceptibly into the zone of Brown soils, and the Reddish Chestnut into the Reddish-Brown soils, where short grasses are dominant and shrubby plants characteristic of still drier regions fairly common.

The Sierozem (gray-earth) soils are in a still drier climate with a dominant cover of sagebrush and only a sparse growth of short grasses. This zone is not very distinct and is considered to be just a little more moist than true Desert and a little drier than the zone of Brown soils. The break between Sierozem soils and Desert soils is approximately the break between the complex of sparse short grass and sagebrush and the zone where desert shrub plants, like creosotebush, shadscale, or white bur-sage are dominant, and grass is almost nonexistent.

Soils in semiarid regions generally are not covered completely by grass. Bare spots are subject to erosion by wind and water and to beating by the occasional torrential rains. The wind removes fine soil from the bare spots, deposits some of it in adjacent grassy patches, and carries the rest greater distances to form dust deposits, frequently in Chernozem and Prairie soils zones. The ultimate result is that the surface of the land in semiarid regions has a peculiar micro-relief with minute basins a few inches deep interspersed between grassy mounds a few inches high. Where soils contain pebbles or rock fragments, these are left behind to form a cover or pavement that protects the soil from further wind erosion.

One or more groups of soils within each soil zone have peculiar properties that set them apart from soils considered "normal" for that zone. Usually one or more horizons of each of these soils is overdeveloped and in marked contrast to the normal soil. These are called intrazonal (within-zone) soils. Planosols of the Prairie and Chernozem soils zones, and claypan soils (some of which are known technically as Solonetz and solodized-Solonetz) of drier regions are intrazonal soils characterized by grassy vegetation. The most extremely developed of the Planosols have very thin surface horizons of dark-colored material rich in organic matter. Beneath the thin dark horizon is light-colored, friable, platy material, several inches thick, with little organic matter, and usually moderately to strongly acid in reaction. Beneath is a strongly developed clayey horizon, or claypan.

While the claypan may appear to be practically impervious, it is easy to demonstrate that grass roots will pierce it if nutrients and moisture are there to attract them. E. G. Fitzpatrick, formerly soil scientist of the Division of Soil Survey in the Department of Agriculture, once made root counts in a claypan soil of Oklahoma. He found more roots in the claypan layer than in the friable silty leached soil immediately above it.

Furthermore, dry weather so shrinks and cracks many of the claypans that water penetrates them readily following dry weather. Grass roots work their way between the blocky- and prismatic-structured particles into deeper layers of the subsoil in search of moisture, and some of the roots actually pierce the dense blocks and prisms of clay. Such penetration tends to lessen the undesirable physical conditions of the soil. Shrinking and expanding of the clay blocks with changes in moisture have the effect of flattening the roots, but this process does not kill them except where extreme shrinkage in dry weather breaks them asunder. Only in soils with subsoil horizons very low in plant nutrients and moisture do the roots fail to penetrate the claypans. But roots generally encounter considerably more difficulty in penetrating claypans than friable soil layers.

All gradations of claypan soils exist from those in which there is a well-developed gray layer like the one described to one in which there is only a thin sprinkling of light-gray silt on the aggregates at the top of the claypan subsoils. Under like climate, the claypan soils with only the beginnings of a gray layer have a more dense grassy vegetation than those in which the gray layer has become well developed. The development of a thick gray layer above the claypan usually is interpreted as evidence of soil deterioration.

Morphology of solodized-Solonetz soils of the drier regions resembles that of Planosols. Most solodized-Solonetz soils have a less dense grass cover than most Planosols. Many of them have innumerable small bare spots where wind erosion has removed the surface horizon and has exposed the intractable clay subsoil. These "scab spots" or "slick spots" are abundant in areas of imperfectly drained soils of the semiarid plains from southern Texas to northern Saskatchewan and Alberta, and in the drier grasslands of California and the Pacific Northwest.

A peculiar group of intrazonal soils known as Rendzinas occurs in regions ranging from subhumid climates where Chernozems are normal to humid climates where leached, strongly acid, light-colored forest soils are dominant. These soils are covered largely with grass and other herbaceous plants and have dark-colored, thick surface layers much like those of the Chernozems. They are developed in soft calcareous clays, marls, and chalk deposits (soft powdery limestone), all of which contain much soft carbonate of lime. It seems that the excessive amount of easily available lime carbonate and the clayey texture of the parent material encouraged the growth of grasses at the expense of forests. Only where soils of this kind have been exposed for a long time to leaching without erosion do the soils become acid and the forests invade the grasslands. The Houston soils of the "blackland prairies" of Texas, Mississippi, and Alabama are good examples. These soils are generally more fertile than the associated strongly acid forested sandy soils.

The Rendzinas in scattered belts of the Southern States from central Texas to Alabama are nearly black in color, but they contain less organic matter on the whole than Chernozems and

Prairie soils of similar colors in the North Central States. It is generally thought that the higher temperatures of the South accompanied by greater activity of bacteria keep the organic material of the soils at a somewhat lower percentage than in grassland soils of the cooler Northern States.

Azonal soils are those which are so young that they have not yet developed distinct soil horizons. The group includes soils with only the beginnings of organic accumulation in the upper layers where grass roots are abundant. Many of these soils are younger than 100 years. The development of older ones has been retarded by rapid geologic erosion on steep slopes or accumulation of sediments on flood plains.

J. E. Weaver and F. W. Albertson have demonstrated the harmful effects on the soil brought about by the invasion of the bluestem prairie by western wheatgrass during and immediately after the great drought of the mid-1930's. Western wheatgrass lacks the dense mass of fine leaves characteristic of the bluestems and so permits the beating rains to destroy the soft crumblike soil aggregates at the surface. The soil runs together and prevents rapid penetration of water. As a result, the soil absorbs less of the rain water, runoff is promoted, and erosion is accelerated. In this way drought conditions are maintained longer than would be expected otherwise.

Forested Soils and Deserts

While it is altogether possible that the total percentage of living and dead organic matter of soils of many forested areas is equal to or greater than that of the Chernozem and Prairie soils, the organic matter of most forest soils is not quite so dark-colored as that of the grasslands and is distributed through greater thicknesses of soil materials.

Probably, also, the ratio of humified soil organic matter to roots in most forest soils is less than in the grasslands. Generally speaking, the majority of forest soils of the United States are light-colored except for a very thin layer immediately under the decaying leaves of the forest. The important exceptions to this are in the Brown forest soil and a few areas of forested Rendzinas, which have dark-colored surface soils not greatly different in superficial appearance from the Chernozem.

The usual explanation for this difference between the black soils of the Prairie and Chernozem zone and the light-colored soils of the forested areas is that the organic matter of the grassland soils is developed largely through the decay in place of myriads of grass roots rather evenly distributed through the soil, and secondarily by the decomposition of grass tops which die back annually. Every year a certain proportion of grass roots, varying with species, and all of the tops, decay and become mixed with the soil. Part of the material disappears as gas, part of it seeps away in ground water solutions, and part of it remains behind in the form of dark-colored, fairly stable, organic matter. The amount of grass roots thus contributed annually to the soil decreases with decreasing rainfall westward across the Plains. Certain roots of grasslike plants like those of the sedge commonly called black root decay so slowly that their contribution to humified soil organic matter is very little, indeed. It is possible to identify the roots of this sedge in Brown soils of the Great Plains many years after the plants have been killed by plowing.

The differences in the amount of organic matter between the dark-colored grassland and light-colored forested soils is ascribed partly to the fact that forest soils are generally more acid in reaction than grassland soils. The "mild" or nonacid humus of grasslands is more stable than the relatively soluble acid humus of forests. Part of this difference may be due to the fact that the molds (fungi) are more active in the organic matter of forest soils than bacteria, whereas the reverse is true in most grasslands.

Grasses will survive better than forest trees in subhumid and semiarid re-

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gions in soils of clayey textures, so that we find many areas of grasslands in heavy clayey soils surrounded by forests on soils of medium to sandy texture. Examples of this may be seen in Texas, where the forested Cross Timbers areas are interspersed with grass-covered Rendzina soils. Furthermore, grassland parks have persisted within areas of forests where subsoils are very droughty, as on some of the gravelly and sandy outwash deposits of northern Indiana and southern Michigan.

Deserts of the United States generally are not grassy, although certain species of grasses are able to survive in some regions commonly called desert. Even in the Yuma Desert of Arizona where rainfall averages less than 5 inches a year, bunchgrasses can be found on certain sandy soils.

None of the desert plants can support a dense growth of fine roots in upper soil layers for any long period of time and so provide enough organic matter to darken the soil appreciably. Furthermore, vegetation in the desert nowhere covers the soil sufficiently to prevent erosion by wind and water. Fine-textured soil materials are removed by the wind or washed away by the occasional rains. Sand is heaped up by the wind around clumps of brush or cactus and silty materials are carried farther to be deposited in denser vegetation around the desert border. Where soil materials contain coarse rock fragments, these are left behind to form a "desert pavement" which helps to check further erosion. As a net result, desert soils contain less organic matter than soils of grasslands.

Medium-textured Desert soils with well-balanced mineral nutrients can become just as productive under irrigation as grassland soils of similar texture, but this can be achieved only after the organic material and nitrogen content have been built up through good agricultural practices.

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THE TOOLS OF FLOOD CONTROL

HUGH H. BENNETT

FLOOD CONTROL begins where the rains fall and runoff originates. Flood control ends only when that runoff has safely reached the ocean.

The work, then, of preventing floods (which annually cost citizens of the United States 250 million dollars in crops, equipment, and other property damage) does not consist only of installing major engineering works along the main channelways of our trunk streams. It consists also of treating the land surface in such a way as to obtain maximum infiltration consistent with proper use of land for crops, pasture, forest, and other purposes. It covers the orderly disposal of runoff from fields, pastures, and woodlands through stabilized waterways and the temporary detention of runoff in small upland storage basins and temporary pools where practicable. It requires, too, the control of the erosional debris—silt—that shoals waterways, fills ditches, and reduces the capacity of flood-control reservoirs.

Sometimes it involves the improvement and maintenance of minor stream channels. In many watersheds large detention reservoirs are required at critical locations to hold back excess floodwaters that would otherwise over-